

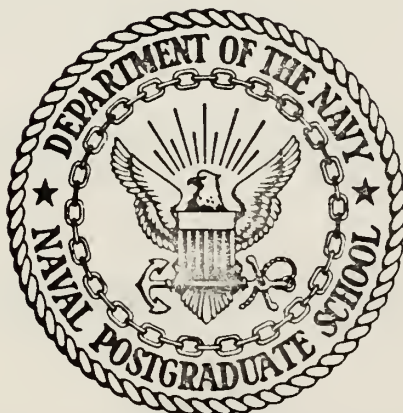
SMOKE AND HELIUM BUBBLE VISUALIZATION
STUDIES OF INCOMPRESSIBLE FLOW
PAST A JET-FLAP AIRFOIL

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THESIS

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STUDIES OF INCOMPRESSIBLE FLOW
PAST A JET-FLAP AIRFOIL

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ABSTRACT

An exploratory visualization study was performed on a jet-flapped airfoil in the Low Speed Flow Visualization Facility at the Naval Postgraduate School, Monterey, California. The purpose of this study was to evaluate the test facility for future work and to compare an old and a relatively new flow visualization technique. These techniques are smoke flow and helium bubble flow. The study was conducted using various tunnel speeds and blowing rates for the jet flap. The varying of these parameters and the complexity of the jet flap flow allowed for an excellent evaluation of the test facility and the two flow techniques. As a result of the many photographs taken, a comparison was made between predicted jet stream deflection, using Spence's Theory, and those deflections measured on photographs.

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TABLE OF SYMBOLS

V	tunnel velocity at test section, ft/sec.
C_j	jet momentum coefficient, $(J/\frac{1}{2}\rho V^2 c)$.
y_c	chord lengths below extended chordline.
	jet angle, angle between the free stream and jet direction at trailing edge, degrees.
J	jet thrust, lb.
c	airfoil chord, ft.
ρ	freestream air density, slugs/ft ³ .

ACKNOWLEDGEMENTS

Grateful acknowledgement is made of the knowledge and assistance afforded me by Professor M. F. Platzter of the Naval Postgraduate School Aeronautical Engineering Department. Also, the technical advice and help of Mr. Stan Johnson was of immeasurable worth in conducting this study.

I. INTRODUCTION

A considerable effort is presently being devoted to the development of high-lift systems for use on STOL airplanes. A recent comprehensive survey has been given by B. H. Wick and R. E. Kuhn in Reference 1. Jet flap systems or jet flap derivatives (such as the augmentor wing) seem to hold great potential for practical implementation as efficient high-lift systems. Also, jet flap systems are being studied now as rapid lift and moment generators for use in gust alleviation and structural dynamic response control systems (Ref. 2).

The purpose of the present investigation was threefold. Firstly, an exploratory visualization study of the incompressible flow characteristics of jet-flapped airfoils was to be carried out. Secondly, further work was needed on the development of an efficient smoke flow visualization technique. Since the Naval Postgraduate School Visualization Facility was only completed in 1971, little prior experience was available in this facility. Thirdly, an evaluation of a new flow visualization technique which recently became available under Office of Naval Research sponsorship -- the helium bubble technique -- was to be conducted and applied to the jet flap problem.

These two techniques as well as their use in visualizing incompressible flow past jet-flapped airfoils are described in the following sections. The results are discussed and evaluated in detail with recommendations for further improvements.

II. LOW SPEED FLOW VISUALIZATION FACILITY

The Low Speed Flow Visualization Facility at the Naval Postgraduate School is essentially a three-dimensional smoke tunnel as shown in Figure 1. This facility is modeled after the one described in Reference 3. The air inlet is a square bell shaped configuration containing a honeycomb three inches thick followed by one layer of screen. The inlet area is 15 x 15 foot and subsequently contracts to a 5 x 5 x 12 foot square test section.

The air flowing through the test section passes through a set of louvers downstream of the section (Fig. 1) and transitions from a square to a circular cross section. Behind the louvers in the circular cross section is a fan that controls the air flow through the tunnel. Between the louvers and the fan is a rubber sleeve to prevent the motor vibrations from being transmitted into the test section. The fan is driven by a motor mounted directly behind it. The air after passing through the fan is turned vertically upward and vented to the atmosphere outside the building.

The roof of the test section has three rows of six lights mounted above plexiglass panels. These panels could be used for observation or lighting of the test section but this area was not used in this study. One side of the test section has a plexiglass window in order to observe or photograph the model. To the right of this window is a door for entering the test section. The opposite wall of the test section is painted

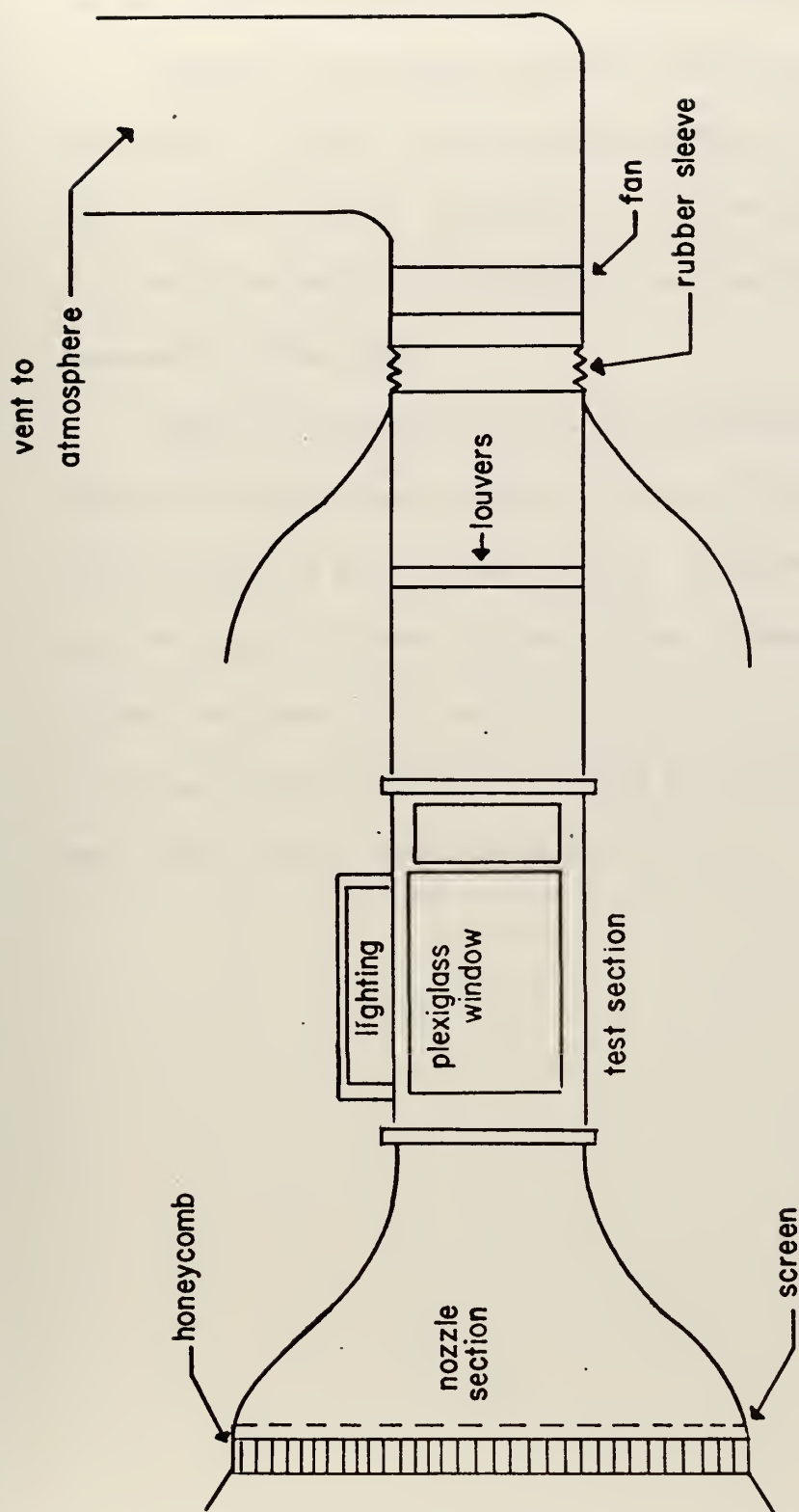


FIGURE I. SCHEMATIC OF NAVAL POSTGRADUATE SCHOOL FLOW VISUALIZATION FACILITY.

flat black for improved photographic contrast. The actual lighting of the test section will be discussed later in detail.

Pictures of both flow techniques were taken with a Polaroid camera using ASA 3,000 film. For the smoke pictures the camera setting was f8 at 1/30 of a second whereas for the helium bubble pictures it was f4.7 for 15 seconds. Shorter times were tried and are described in Section VII of this paper.

Since the turbulence level in this tunnel was definitely to have an effect on this study and all future studies, it was decided to measure the level using a hot-wire anemometer. The anemometer and components used were built by Thermo-Systems, Inc. of Saint Paul, Minnesota. The highest turbulence level measured was 1.7% at a tunnel velocity of 4 fps. In the speed range covered (6 - 32 fps) for this study the highest level was 0.97% and the lowest level was 0.47%.

III. SMOKE FLOW VISUALIZATION TECHNIQUE

The first method to be evaluated was smoke flow visualization since this method had been very successful in the past for airstream phenomena. Since the flow visualization facility at the Naval Postgraduate School had not been extensively used previously, the lighting and visualization medium had not been perfected to a satisfactory level.

Several methods of producing smoke were known from Reference 4 such as burning hay, fuming titanium tetrachloride in air, and oil smoke. The burning hay and titanium tetrachloride methods were not considered suitable because of the inherent corrosive effect on the models. Oil smoke and kerosene were the only substances looked into as recommended by both A. M. Lippisch (Reference 5) and F. O. Ringleb (Reference 3). Both the mineral oil and kerosene produced the same quality of smoke. The smoke generator tested was somewhat like the version employed by Preston and Sweeting, as well as by Ringleb, and is pictured in Figure 2. It consists of five Pyrex jars each of whose lids have four openings with rubber stoppers. Through one of these openings an air line enters. From another the smoke emerges into a collecting chamber. In the top center hole oil is put in as desired to cover the wire coiled at the bottom of the jar. The last hole in the lid is for the electric wire to the coil. The coil is heated by passing six volts through it, thus producing the desired temperature to generate smoke vapor. It

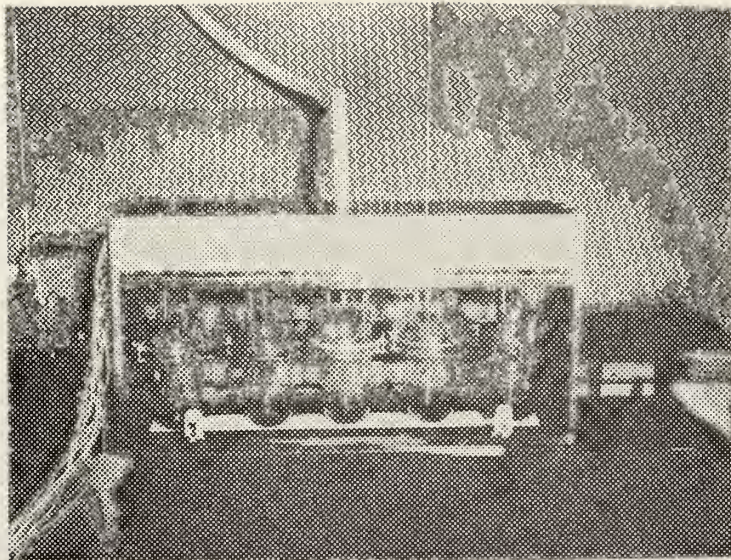


Figure 2. Smoke Generator.

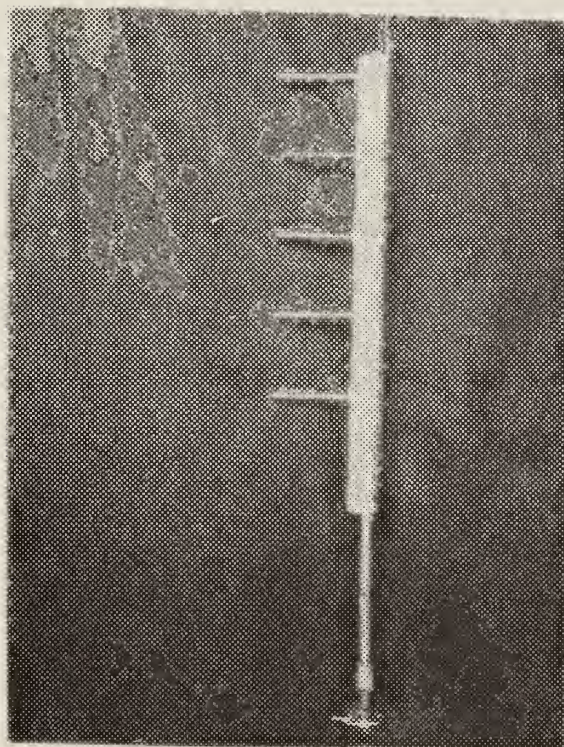


Figure 3. Smoke Ejector.

is important here that the air entering the jars be cool so that it would cool the oil fumes and thus produce the smoke by condensation.

The voltage required for each bottle is centrally controlled by five independent rheostats, one wired to each bottle. This proved to be very advantageous in order to control the amount of smoke desired and also to prevent possible overheating or glowing of different coils.

The smoke from the collecting chamber leads to a smoke rake (Fig. 3) which was mounted in the tunnel for preliminary tests. Since this was the first extensive testing of this particular flow visualization facility, various locations for the smoke rake were tried. Initially the rake was mounted about 2.5 feet upstream of the flow visualization section. In this position the desired streamlines were much too wide and scattered at all speeds. Since this tunnel is almost an exact duplicate of the one used at the Naval Air Engineering Laboratory in Philadelphia, it was decided to mount the rake upstream of the honeycomb as done in Philadelphia, although it had been tried in this tunnel before unsuccessfully. Again with further testing this proved to be unsuccessful.

Further studies of other tunnels built on a smaller scale showed that there was a definite need for several layers of screening upstream and downstream of the honeycomb in order to reduce the level of flow turbulence and straighten out the smoke lines. Therefore, it was decided to mount a 15 foot x 15 foot piece of sectioned screening on the downstream side of the honeycomb. This proved to be very successful in

generating the desired vortex flow of the smoke streamlines as described in Reference 6. From the results of mounting this one screen it is easily seen why three or more screens are recommended in Reference 7.

For the initial studies of the smoke flow visualization, the overhead lights already installed above the tunnel (Figure 1) were used but for photographic purposes this lighting proved to be unsuited even with high-powered photo spot lights. Since a good lighting system was desired for this particular tunnel, many different locations were tried. Finally, it was recommended by Mr. Howard Bench from the Photo Department of the Office of Educational Media to mount two Colortron movie lights behind the smoke lines upstream and downstream of the test section (Figure 4). These special lights positioned behind the flow proved to be the optimum for both still pictures and black and white movies. Presently the only disadvantage to these lights is their size and present position in the tunnel. For future work in this flow visualization facility, the lights should be mounted in the walls behind glass or plexiglass.

As mentioned earlier, one screen had a significant effect on the flow. The exact reason can be found in a study done by Dryden and Schubauer at the National Bureau of Standards in 1940 (Ref. 7). In this study, extensive testing of one, two, three, four and six screens in series was performed to find the effect of screen mesh size, number of screens and spacing between screens on the turbulence level. It was found that the turbulence level was reduced from 0.54 to 0.19 percent

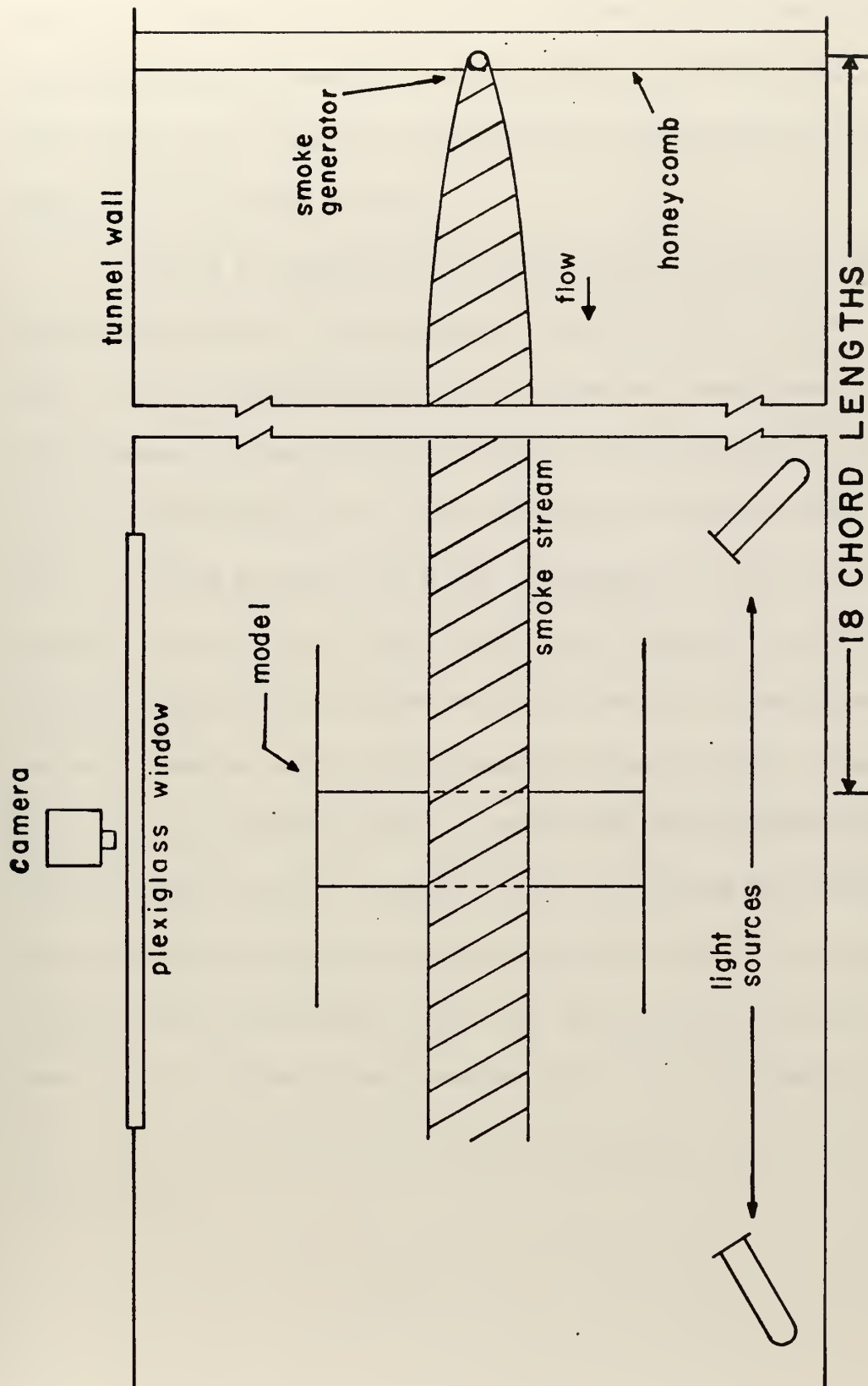


FIGURE 4. SCHEMATIC FOR SMOKE FLOW PHOTOGRAPHY.

with the addition of just one screen. Further results showed that the spacing between screens had no measurable effect on the results and that there was no significant improvement in the turbulence level when using more than three screens.

It should be explained at this time that the decision to put the one screen downstream of the honeycomb is based on the results of Ringleb (Ref. 3). As mentioned earlier, this tunnel is in many ways a duplicate of his tunnel and he found that no perfect smoke stream line could be obtained without this one screen downstream of the honeycomb. However, it should be kept in mind that the purpose of the screen is to "smooth" the air stream to the extent that it decreases turbulent motion of larger scale than the screen mesh size, while introducing turbulent motion of smaller scale which fortunately decays rapidly. Therefore, it is felt that putting the screens upstream of the honeycomb defeats the purpose of the screens. Ringleb's reason for putting five screens upstream of the honeycomb is not clear from his report, but as noted above he did not get good results until he put the one screen downstream of the honeycomb. In other tunnels studied (Refs. 6, 8, 9), the screens were all located downstream of the honeycomb and good results were obtained in all cases.

IV. HELIUM BUBBLE FLOW VISUALIZATION TECHNIQUE

The helium bubble technique of flow visualization is still in the experimental stages of development and evaluation by several organizations. Sage Action Incorporated of Ithaca, New York, builder of the unit used at the Naval Postgraduate School, is presently conducting two studies for the Office of Naval Research using this technique. Their efforts are aimed at the study of complex flow phenomena and transonic flow problems. The Rochester Applied Science Associates, Inc. of Rochester, New York, has completed a tip vortex study using this technique and reportedly has obtained excellent pictures of the tip vortex pattern (Reference 10).

The basic idea of the helium bubble flow visualization technique is to implant small bubbles about $1/4$ inch to $1/8$ inch in diameter into an air flow upstream of a model and photograph their motion using special high-speed film. The bubbles are generated at a max. rate of 250 bubbles per second. Since the bubbles are filled with helium and thus almost neutrally buoyant, they should follow any flow faithfully. As will be shown in Section VII, exactly neutrally-buoyant bubbles apparently were not achieved and there is some doubt whether this condition can indeed be realized. Downstream of the model a high intensity light is placed, usually an arc lamp, so that its narrow beam is directed upstream along the bubble trajectories and thus illuminates the bubbles (Fig. 5).

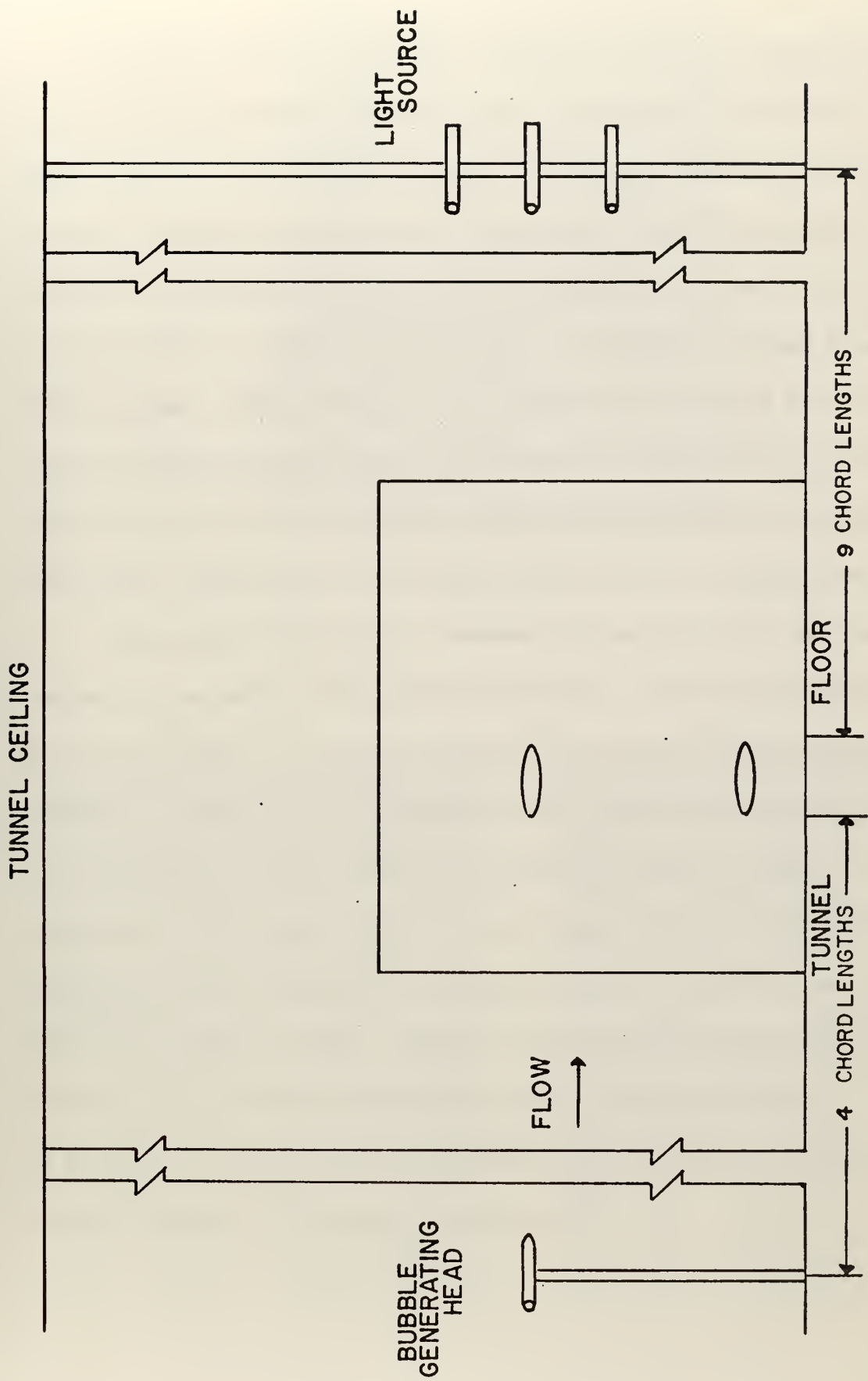


FIGURE 5. SCHEMATIC LAYOUT FOR HELIUM BUBBLE PHOTOGRAPHY.

The unit used in the NPS flow visualization tunnel consists of the Bubble Generator Console (Figure 6) and a Low-Speed Bubble Ejector Head (Figure 7). The complete system is extremely simple and easy to operate. The bubbles are emitted from the head, which is basically a concentric arrangement of three tubes. Helium, air and bubble film solution (BFS) are supplied to the head from the console through flexible plastic tubing. Within the head, the helium passes through the central tube and bubble solution through the intermediate tube to form the helium-filled bubbles at the tip of the BFS tube. Air passing through the outermost tube or shroud blows the bubbles off the tip in a continuous manner.

The console (Figure 6) is a separate unit which meters the flow of helium, air and bubble film solution to the head. External sources of helium at 20 lb/in.² and air at 75 lb/in.² are used. The bubble film solution is stored in a 75cc stainless steel cylinder within the unit and a full cylinder of solution was found to last for about two hours of continuous use. The bubble size and rate of generation can be controlled at the console by adjusting the settings of the micro-metering valves for the air, helium and BFS. The rate of generation goes from 1 to 250 bubbles per second and the bubble diameter can be varied from 1/16 inch to 1/4 inch. A more complete description of the operation of the Helium Bubble Generator can be found in Reference 11.

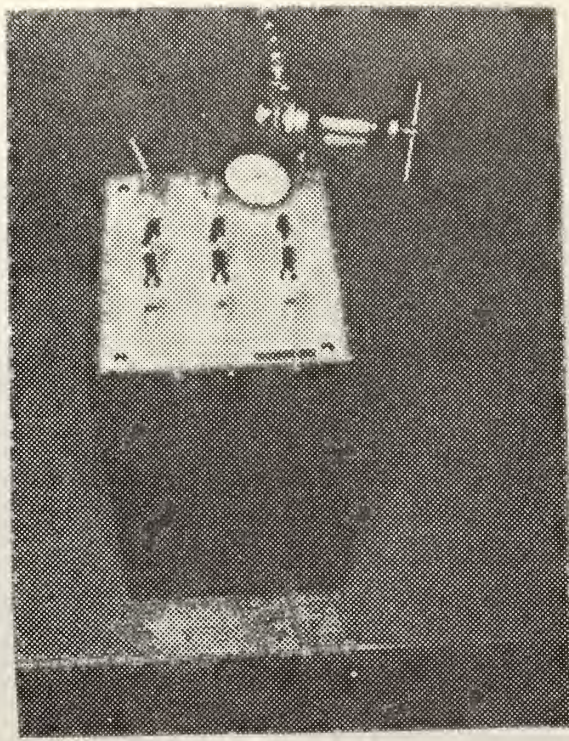
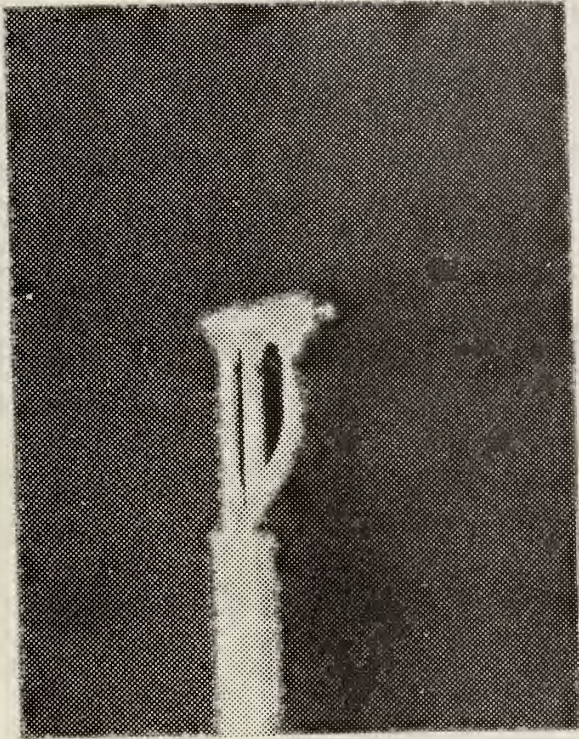
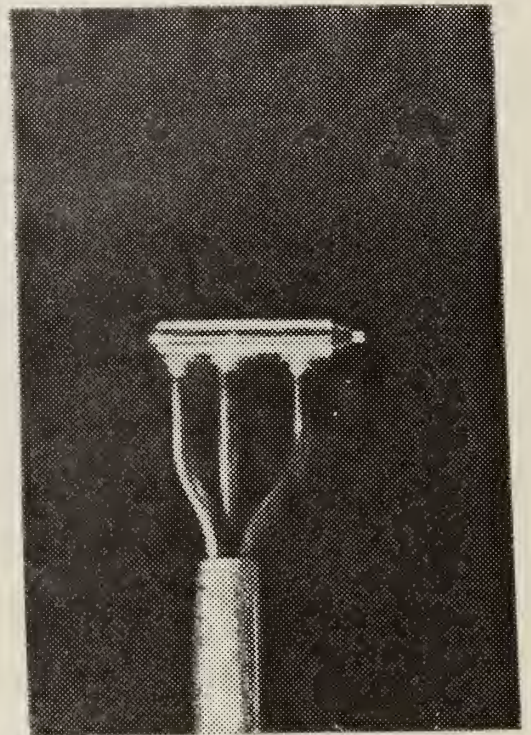


Figure 6. Bubble Generator Console.



a.



b.

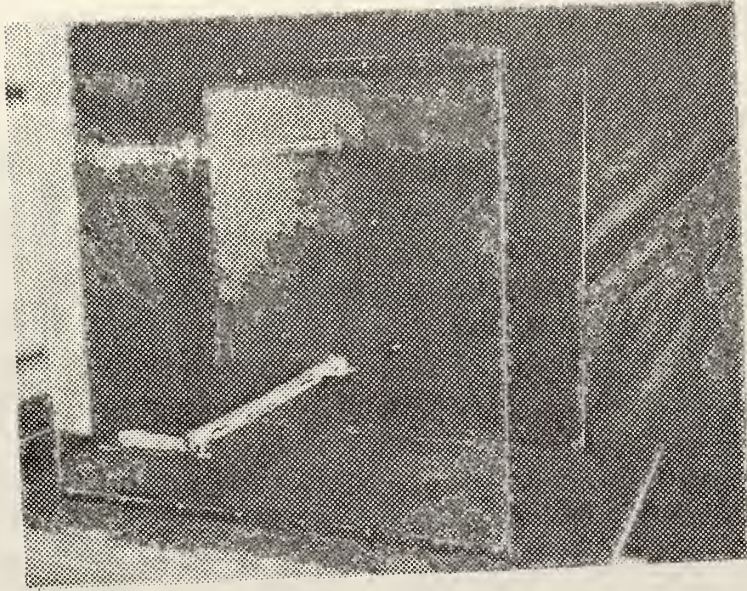
Figure 7. Low-Speed Bubble Ejector Head.

V. JET FLAP MODEL

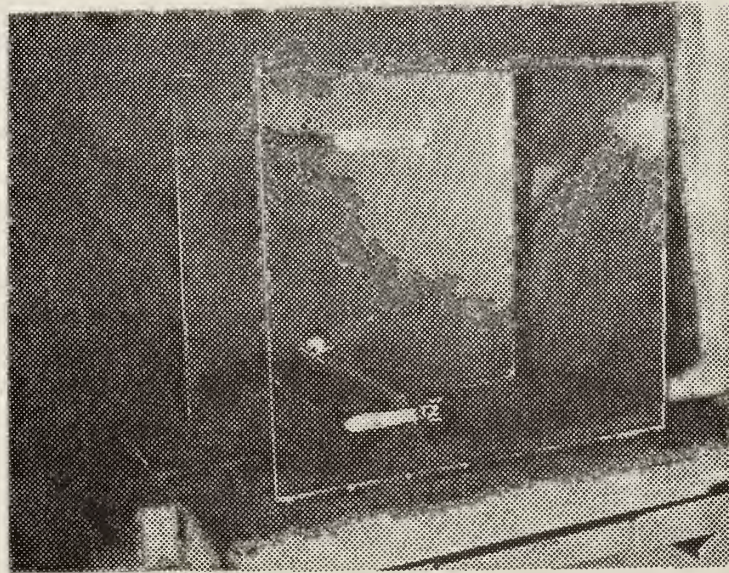
The jet flap is a means of controlling the circulation over an airfoil by ejecting high momentum air from a thin full span slot at the trailing edge of the airfoil. The angle of deflection can be set in one position or oscillated by either a mechanic or fluidic oscillator as recommended by Simmons and Platzler in Reference 2. Also, with two such jet flaps mounted above and below each other an efficient airstream oscillator is possible. The model tested (Fig. 8) has two such airfoils mounted parallel to each other, to be employed as an airstream oscillator in future tests. For the present tests, only the top airfoil was studied and air was blown only from this top airfoil.

By blowing from the trailing edge of an airfoil the circulation around the airfoil is modified. With sufficiently high blowing rates "supercirculation" can be achieved although usually leading edge separation sets an upper limit. This supercirculation reduces the static pressure on the upper airfoil surface and increases it on the bottom surface thus increasing the lift of the airfoil. Also, the jet momentum in the lift direction produces a so-called "reaction lift." A detailed discussion of the jet-flap principle is contained in Reference 12.

In this study a two-dimensional symmetric airfoil with a seven and one-half inch chord, 23 1/2 inch span and NACA 0015 profile was used as shown in Figure 8. The aft 15% of the chord was removed and replaced across the full span by a circular steel tube with a 0.753 inch outside diameter and a 0.672 inch inside diameter as shown in Figure 9. There was no gap between the tube and the airfoil. The tube was free to rotate in bearings at each end and it served as a plenum for the jet flap which was formed by a row of 0.025 inch diameter holes spaced 0.25 inch apart along the trailing edge of the tube across the full span.



a.



b.

Figure 8. Jet Flap Model.

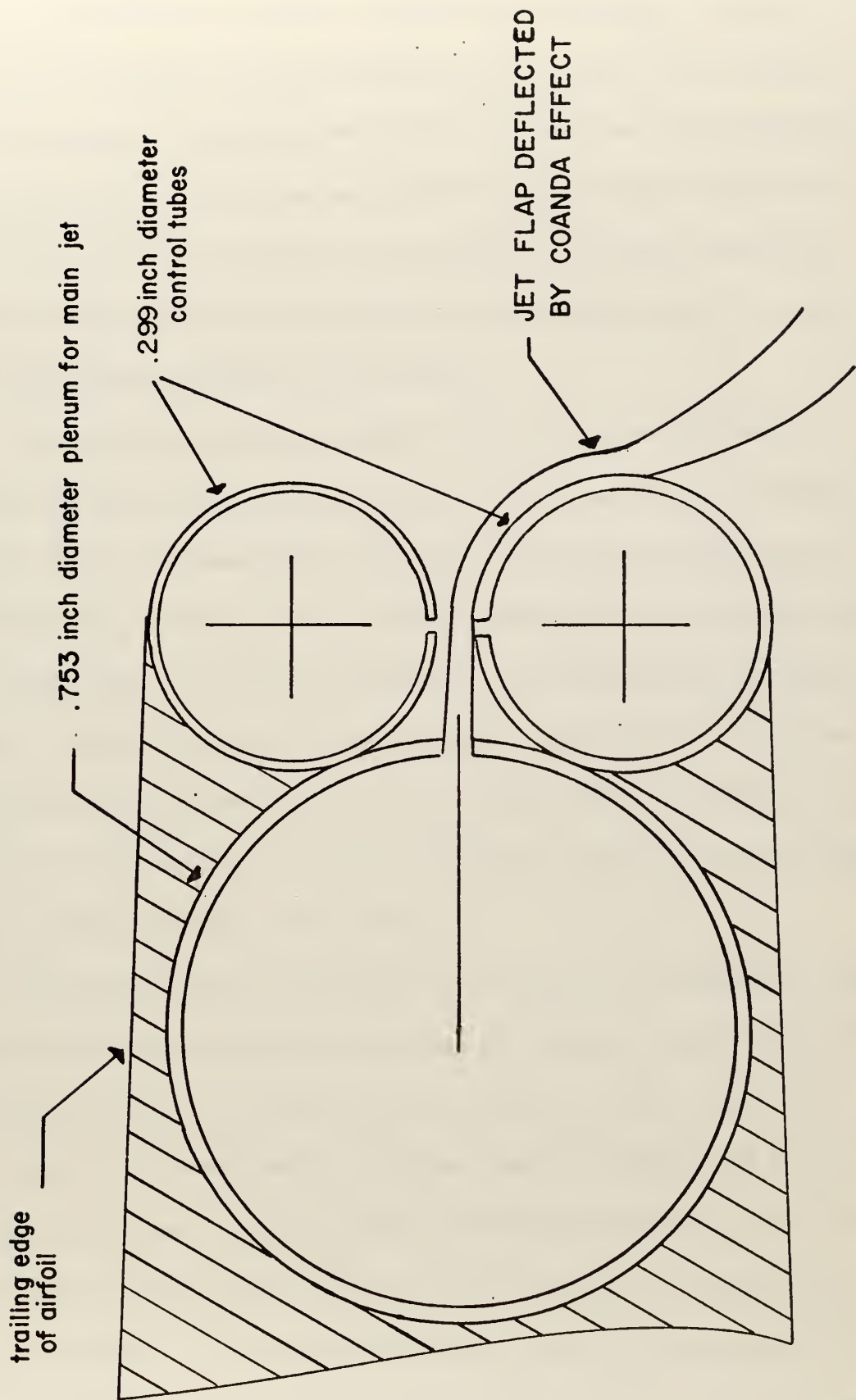


FIGURE 9. SCHEMATIC OF JET FLAP CONTROL.

Air was supplied by an air hose connected to the end of the plenum tube. Figure 8 is a picture of the test apparatus. The airfoil was clamped between rectangular plexiglass end plates to obtain two-dimensional flow over the airfoil. The end plates extend one chord length upstream and 3.29 chord lengths downstream of the airfoil. This test apparatus is modeled after that used by Simmons and Platzer (Reference 2) in their two-dimensional oscillatory flow studies.

Two 0.299 inch diameter fluidic control tubes were fastened across the full span of the trailing edge, above and below the existing plenum tube. The plenum tube was set so that the jet flap was in the airfoil chord plane from which it could be deflected up or down by using the control tubes. Air was not supplied to the control tubes for these tests. Instead, the main tube was rotated so that the air passed over the bottom control tube and due to the Coanda Effect was turned to an angle of approximately 80° from the chordline in still air. This position was maintained through all the tests.

The jet momentum coefficient C_j is used as a measure of blowing rate and indicates the ratio of available jet momentum flux to freestream dynamic pressure. For these tests, jet thrusts of 1.79, 1.065 and 0.645 lbs. were used corresponding to plenum chamber pressures of 37 psig, 20 psig and 10 psig. These thrusts were measured statically on a beam balance system and held constant by monitoring the mean pressure in the plenum tube. At tunnel speeds between six feet per second and 32 feet per second, values of C_j between 0.442 and 34.9 were used and

are shown on each photograph. It should be noted that, because the jet flap consisted of discrete jets, its momentum coefficient was taken as the average value across the span. The actual calculation of the jet momentum coefficient can be found in Reference 12.

VI. COMPARISON OF TEST DATA WITH THEORY

In 1956, D. A. Spence set forth a solution for the inviscid, incompressible flow past a thin, two-dimensional wing at a small incidence, from the trailing edge of which a thin jet emerged at a small deflection angle α (Ref. 13). In this solution, an infinitely thin jet of finite momentum (and therefore infinite jet velocity) is assumed.

Since, previously, very close agreement had been found between Spence's solutions and actual tests by Dimmock (Ref. 14) it was felt that an exploratory evaluation of the enclosed pictures was meaningful. It should be explained first that Spence's solution is based on the assumption that the jet stream emerges at a set definite deflection angle from the trailing edge of the airfoil. Also, Dimmock built his model such that the air emerged at the trailing edge at a definite fixed angle that could not be changed. In the present study this initial deflection angle is much more difficult to define as will be explained below.

The jet of air (Fig. 8) is blown over the curved surface of the bottom control tube. As the attached jet flows over the control surface it entrains mass from its surroundings because the pressure in the jet due to flow curvature is less than atmospheric pressure. Due to this mass entrainment and viscous dissipation the jet thickens, which in turn causes the wall jet pressure to increase. The wall jet finally entrains enough mass to cause the pressure to increase to approximately

the ambient pressure. At this point the jet usually separates from the curved surface. For these tests, the jet remained attached down to approximately 80° from the chordline. This deflection of a plane jet by its adjacent curved boundary is called the Coanda Effect. A good review of this phenomenon is given by Newman (Ref. 15). A schematic of this process is shown in Figure 9.

The deflection angle of 80° , mentioned above, is obtained at zero tunnel speed. When the tunnel is operating it can be seen from the photographs that this deflection angle is appreciably less than 80° . Since the exact point of separation from the control tube is very difficult to determine due to the Coanda Effect as mentioned in References 16, 17, 18, an average deflection angle had to be used. This average deflection angle was taken from each photograph and is listed in column (4) of Table I. However, for a comparison with theory, the deflection angle at the point of separation is needed. It was assumed to be 15° greater than this average deflection angle and is listed in column (5).

Using the unpublished computer program of Lt. Paul Schlein,¹ which is based upon Spence's theory, and with the values of C_j used in the tests, the jet deflection (Y-coordinate) of the thin jet stream was computed one chord length downstream of the trailing edge.

Column (1) of the table gives the figure used for the measurement of the average deflection angle τ in column (4). Columns (6) and (7) give the measured and predicted location of the jet stream below the extended chordline.

¹Work currently in progress.

TABLE I

(1) Figure	(2) V Ft/Sec	(3) C _j	(4) τ Deg.	(5) $\tau+15^\circ$ Deg.	(6) Y _c (Chords) (Measured)	(7) Y _c (Chords) (Predicted)
10	6	20.8	60	75	0.813	1.070
11	6	34.9	60	75	1.010	1.120
12	13	2.7	59	74	1.060	0.749
13	13	4.4	60	75	1.000	0.850
14	13	7.4	45	60	0.870	0.700
16	32	0.4	16	31	0.180	0.156
17	32	0.7	27	42	0.280	0.284
18	32	1.2	28	43	0.350	0.345

It is evident from the Table that more consistent results were found at the high speeds. At the 13 feet per second tunnel velocity, it was very difficult to measure the exact deflection angle or to see a measurable difference when 37 psig or 20 psig were used.

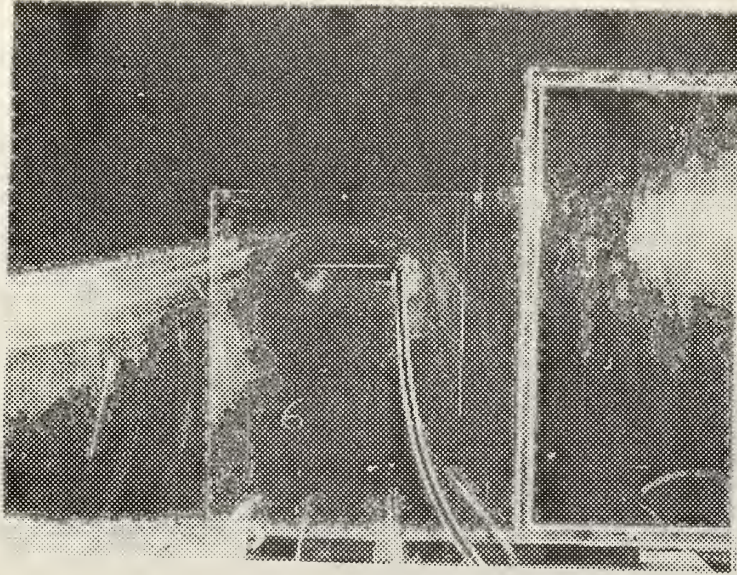
As previously stated, Spence assumed the deflection angle to be fairly small and definite. In this study the still-air deflection angle was 80° and the deflection angles due to the effect of the operating tunnel were estimated to be 16 to 60 degrees. Spence also assumed that the jet stream was very thin, whereas in actuality it has finite width. Consequently, it was necessary to measure approximately where the center of the finite-width jet stream was located. Due to these assumptions, the model used, and the tabulated data from this study, it was felt that no really sound correlation could be made between Spence's theory and the enclosed data.

VII. RESULTS

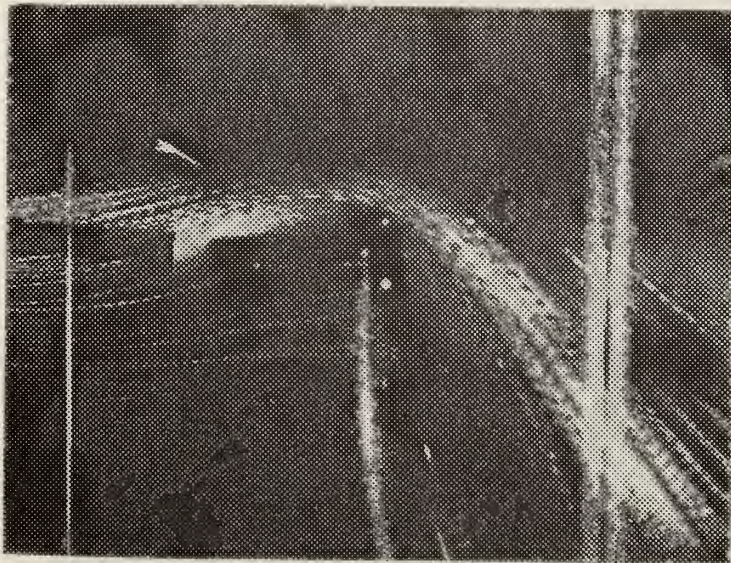
The two methods of flow visualization have been described in detail. It is now possible to look at the results obtained in the NPS Flow Visualization Facility and evaluate the two methods for different tunnel speeds and blowing rates. It must be remembered that the enclosed pictures are in some cases the best of many photographs taken with different lighting situations. As expressed by both Lippisch in Reference 5 and Ringleb in Reference 3, the photography was one of the most difficult areas to master in flow visualization.

It was found with this tunnel, due to its present high level of turbulence, that the lowest tunnel speed for good flow visualization was about 6 feet/sec. Therefore the speed range used was from a low of 6 feet/second to a high of 32 feet/second. In order to adequately cover the tunnel's speed spectrum and the jet flap's possible pressure range, speeds of 6 feet/second, 13 feet/second and 32 feet/second and air pressure of 10 psig, 20 psig and 37 psig were used.

At 6 feet/second, it is evident in Figure 10-a that the smoke is dissipated by the air on the downstream side of the flap, thus no angle of departure could be measured. Also due to the characteristics of the plexiglass and the position of the lights, there was too much glare. In later photographs this glare was reduced. In Figure 10-b more definite streamlines are present than in Figure 10-a. Also, it is readily possible to measure a deflection angle.

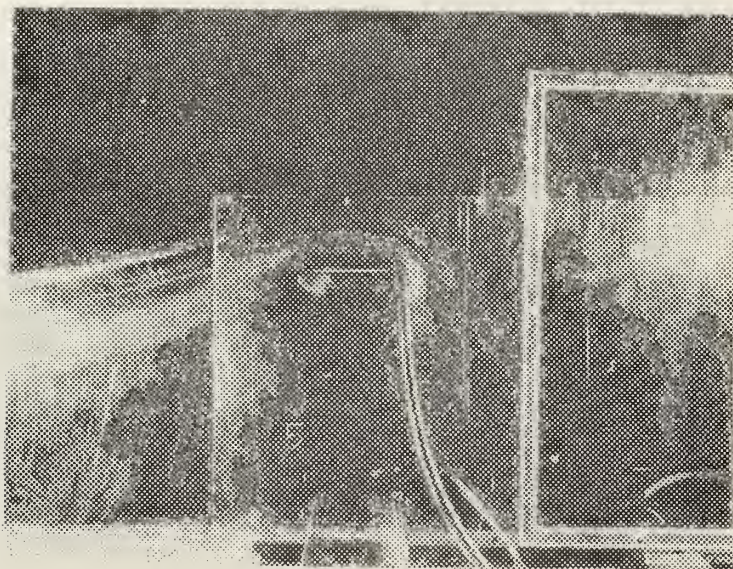


a. Smoke Flow.

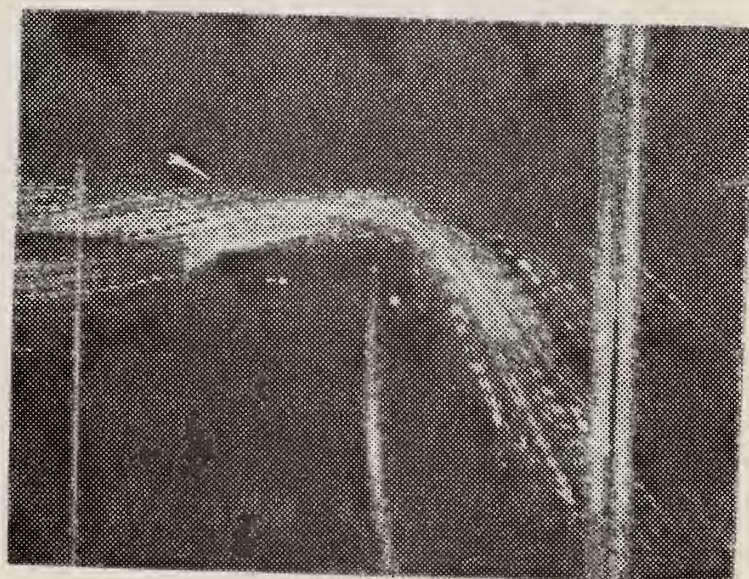


b. Helium Bubble Flow.

Figure 10. $V=6\text{ft/sec.}$; $C_j=20.8$

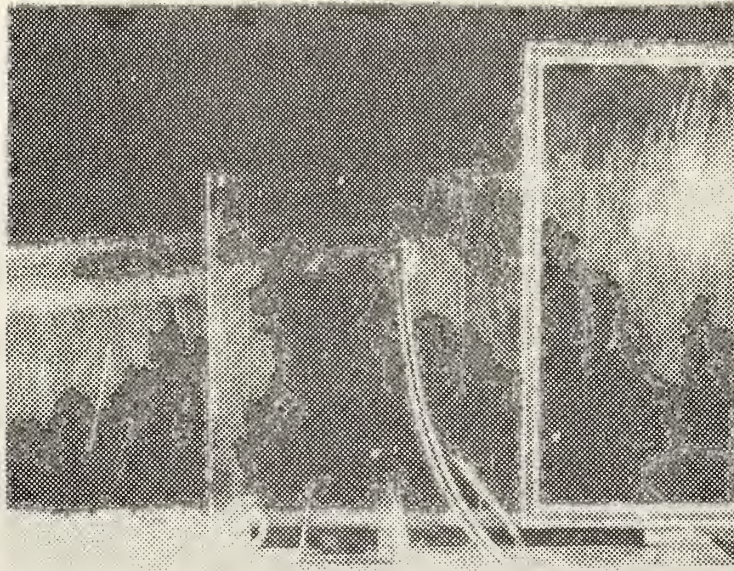


a. Smoke Flow.

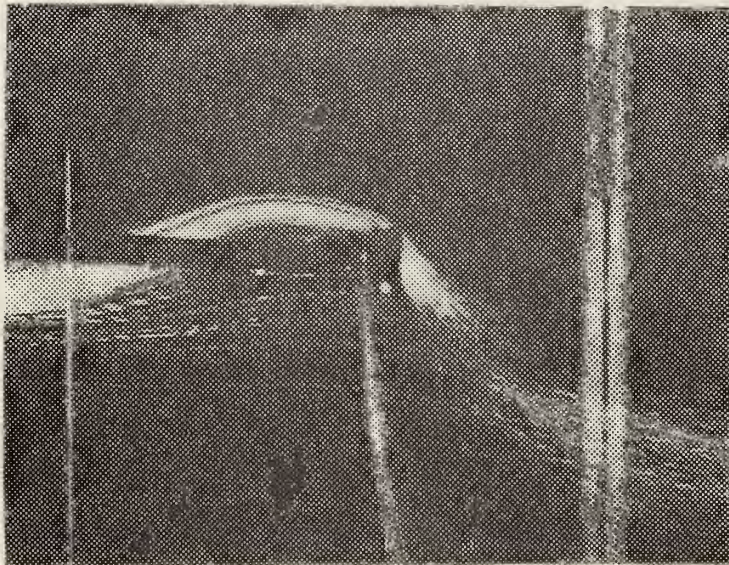


b. Helium Bubble Flow.

Figure 11. $V=6\text{ft/sec.}$; $C_j=34.9$



a. Smoke Flow.



b. Helium Bubble Flow.

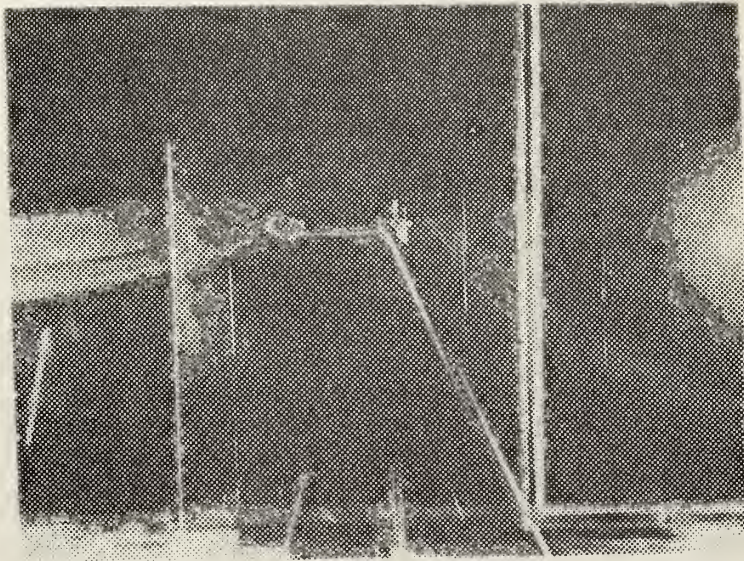
Figure 12. $V=13$ ft/sec. ; $C_j=2.7$

Again in Figure 11-a the smoke can be seen to be dissipated by the high pressure air. In Figure 11-b many stray bubble lines are apparent below the wing. Also, streamlines seem to cross each other above the wing which causes some concern as to whether streamlines are indeed being visualized.

At tunnel speeds below 6 feet/second the helium bubble technique was quite unsatisfactory because at the lower speed the bubble trajectories were too random by the time they reached the wing. If the ejector head could be positioned further upstream, this problem might be eliminated, but in this tunnel this is hardly feasible.

In Figure 12-a at a tunnel speed of 13 feet/second not as much of the smoke was dissipated due to the decreased angle of departure from the trailing edge caused by the higher tunnel speed. Again in Figure 12-b the streamlines are observed to be crossing but in some areas it looks as if the streamlines might be fairly representative of the flow, especially under the wing and off the trailing edge. It is of interest to note here that more light is reflected above the wing than below the wing due to more bubbles moving over the top of the wing and at a higher velocity.

Figure 13-a illustrates a region of separated flow on the wing upper surface, which may be analogous to the separation bubble described in Reference 12. In Figure 13-b the crossing of streamlines is again seen below the airfoil and really no distinct streamlines can be seen over the top although the deflection angle seems to be reasonably well defined.

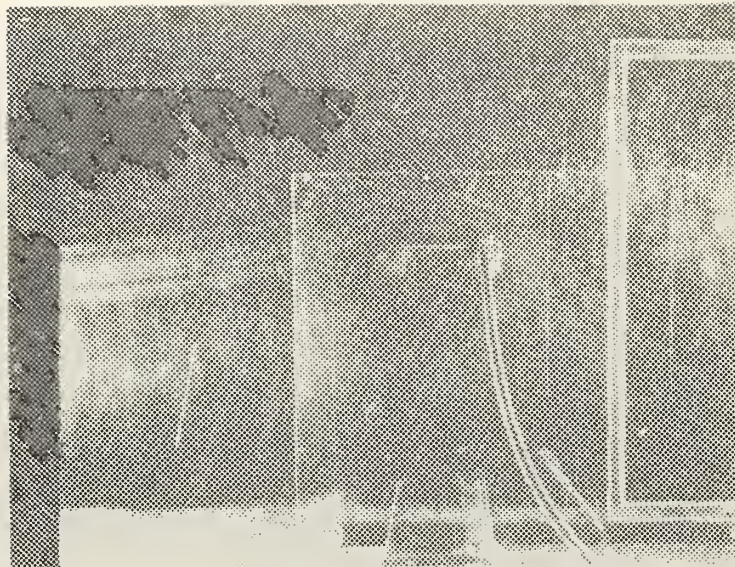


a. Smoke Flow.

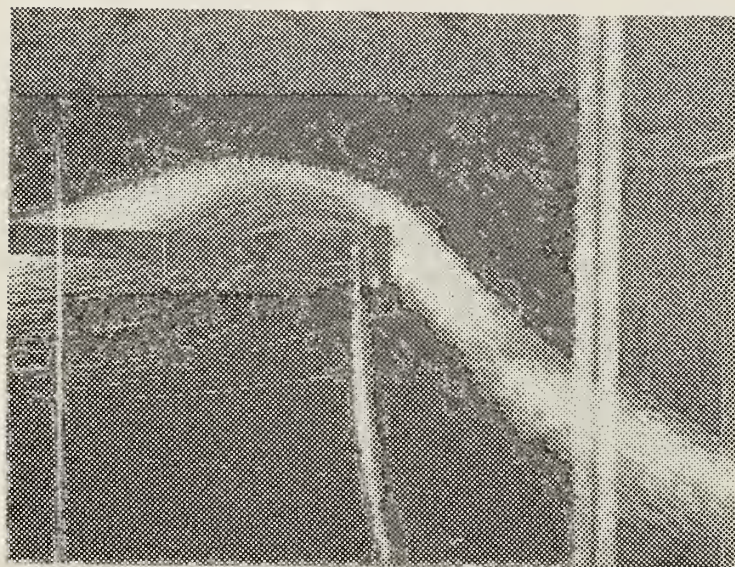


b. Helium Bubble Flow.

Figure 13. $V=13$ ft/sec. ; $C_j=4.4$

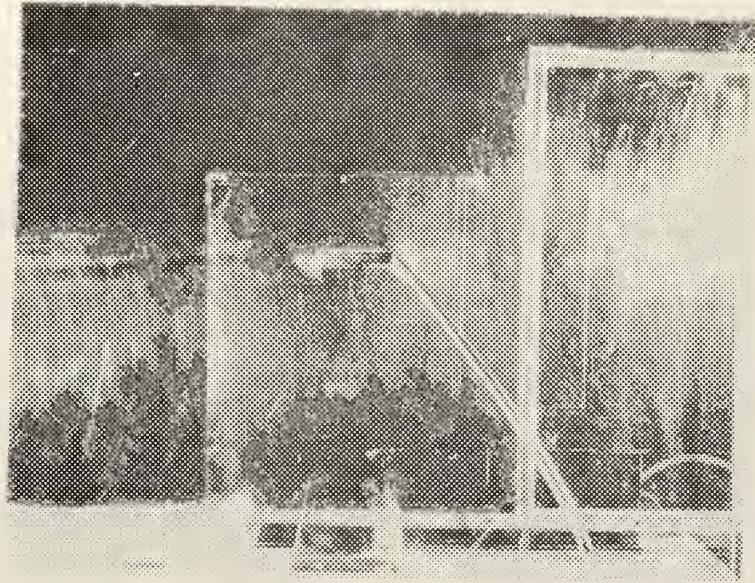


a. Smoke Flow.

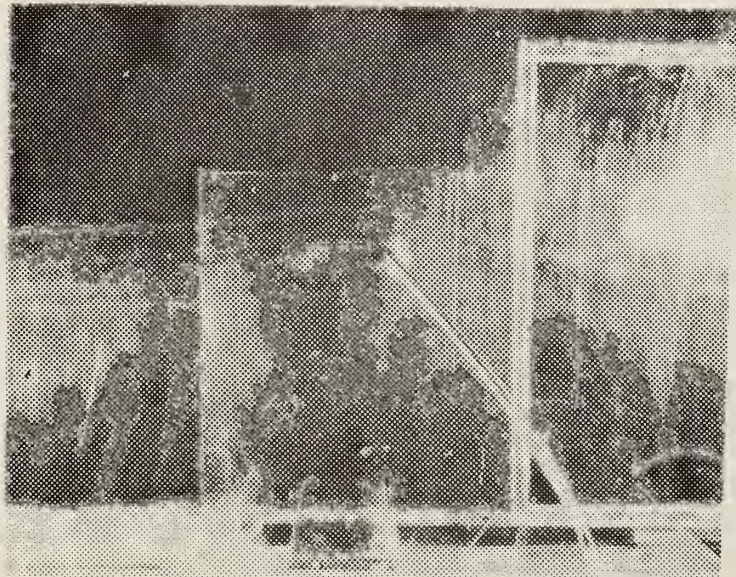


b. Helium Bubble Flow.

Figure 14. $V=13$ ft/sec. ; $C_j=7.4$



a. Smoke Flow.



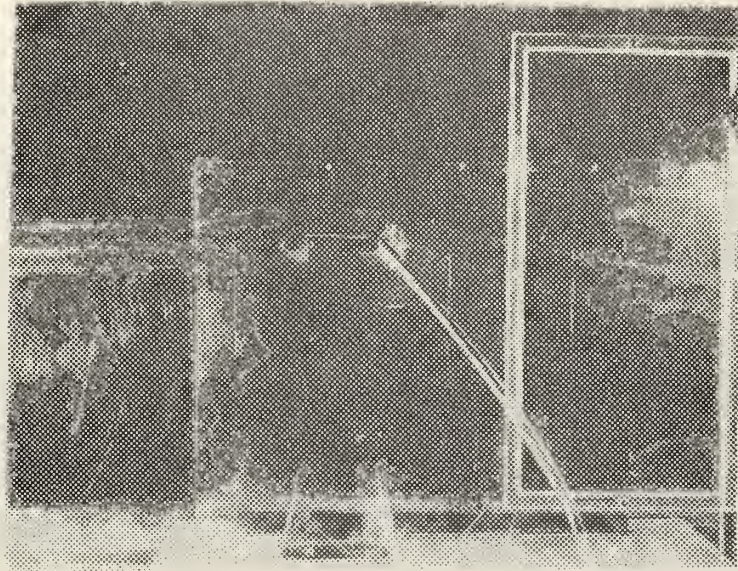
b. Smoke Flow.

Figure 15. $V=32$ ft/sec. ; $C_j=1.2$

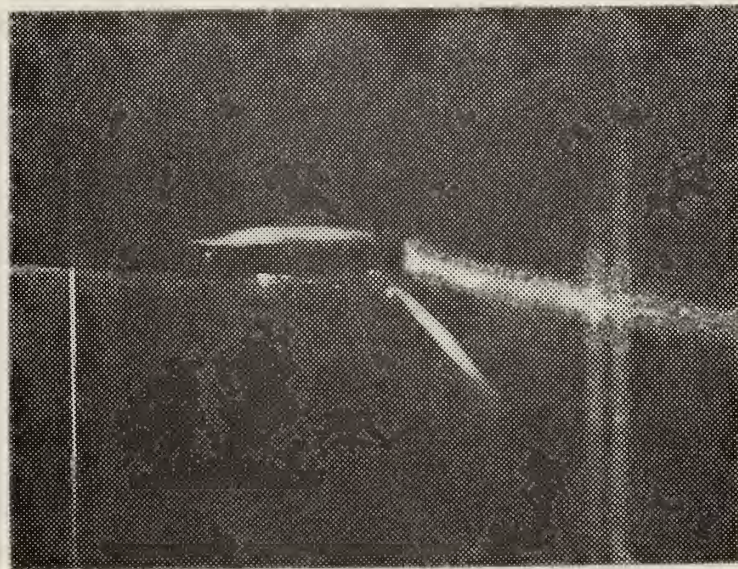
Much more distinct streamlines can be observed in Figure 14-a than in our previous smoke photographs and again a possible separation area on top of the wing should be noted. When comparing Figures 13-b and 14-b, a higher deflection angle and more reflected light from the higher mass flow can be seen in Figure 14-b as a result of the higher C_j . On the top of the airfoil a few lines can be seen next to the airfoil. Therefore, there may not be a separated flow region there.

As mentioned earlier, lighting was definitely a problem to be overcome. Figures 15-a,b are examples of poor lighting for the smoke flow. Distinct flow lines cannot really be seen and there is too much glare on the plexiglass. After the photographs in Figures 15-a,b were taken the lights were readjusted to eliminate some of the glare and to put more contrast on the smoke lines. Figures 16-a, 17-a and 18-a are the result of the adjustment. As can be seen, there is little glare and definite smoke lines.

With the high tunnel velocity of 32 feet per second, very little deflection was caused by the jet at the low pressure of 10 psig. The smoke lines were clear and definite, but the helium bubbles at this tunnel speed and lens opening of 15 seconds cause a blur over the wing. In Figures 17-a,b and 18-a,b the results were about the same. At this higher tunnel speed the smoke was easier to photograph although the helium bubbles gave much better visual flow definition but were difficult to photograph. An example of a fairly good flow picture for the helium bubble technique is Figure 19. Here the streamlines are well defined but due to

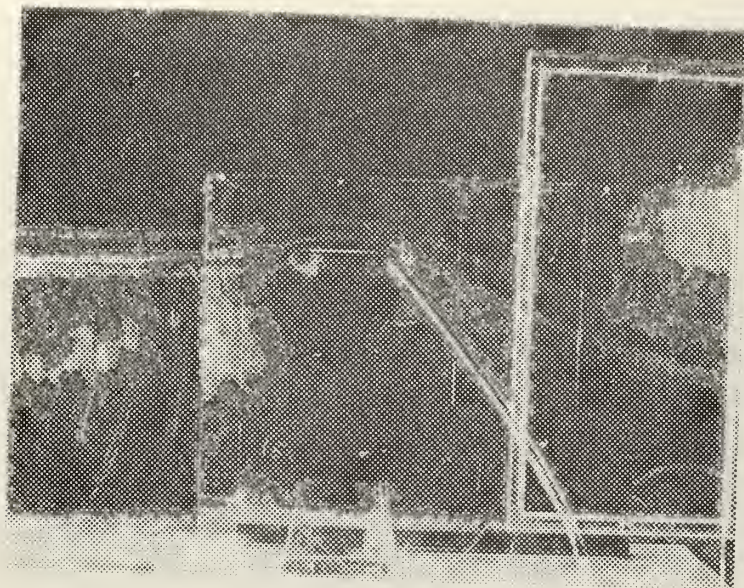


a. Smoke Flow.

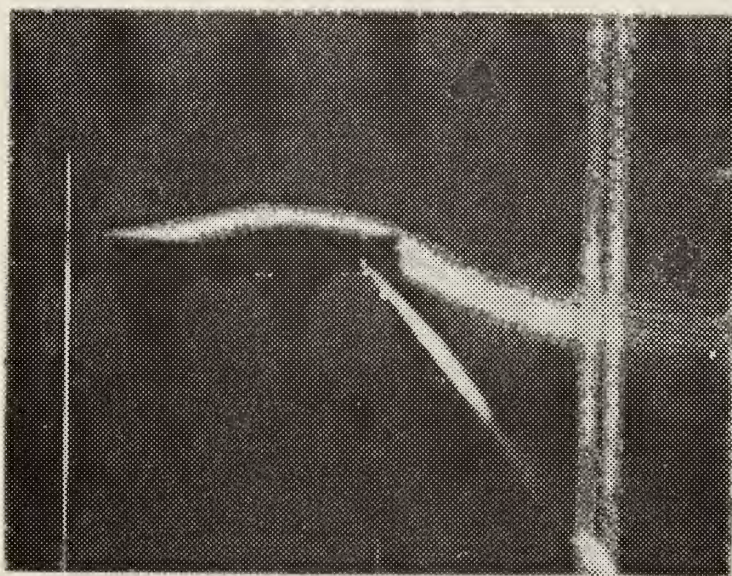


b. Helium Bubble Flow.

Figure 16. $V=32$ ft/sec. ; $C_j=0.4$

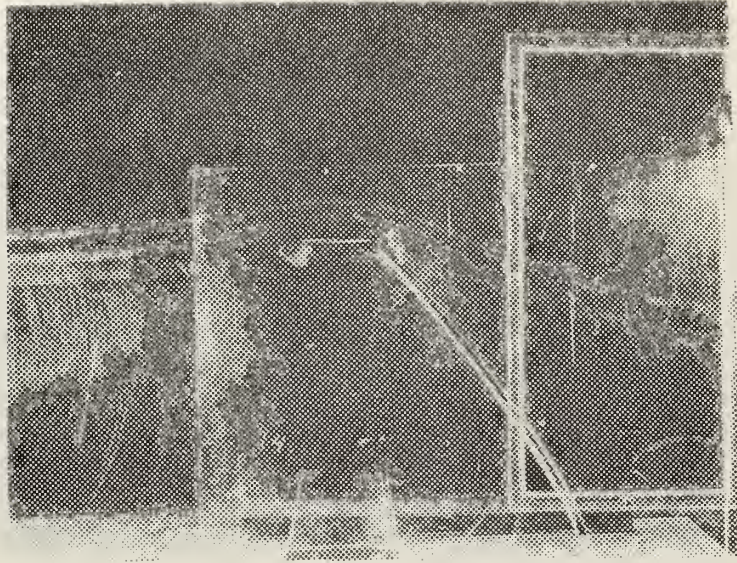


a. Smoke Flow.

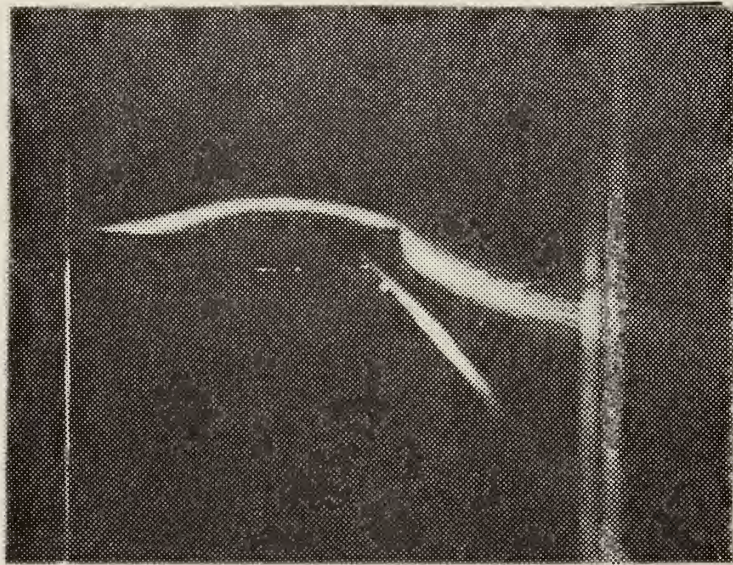


b. Helium Bubble Flow.

Figure 17. $V=32$ ft/sec. ; $C_j=0.7$



a. Smoke Flow.



b. Helium Bubble Flow.

Figure 18. $V=32$ ft/sec. ; $C_j=1.2$

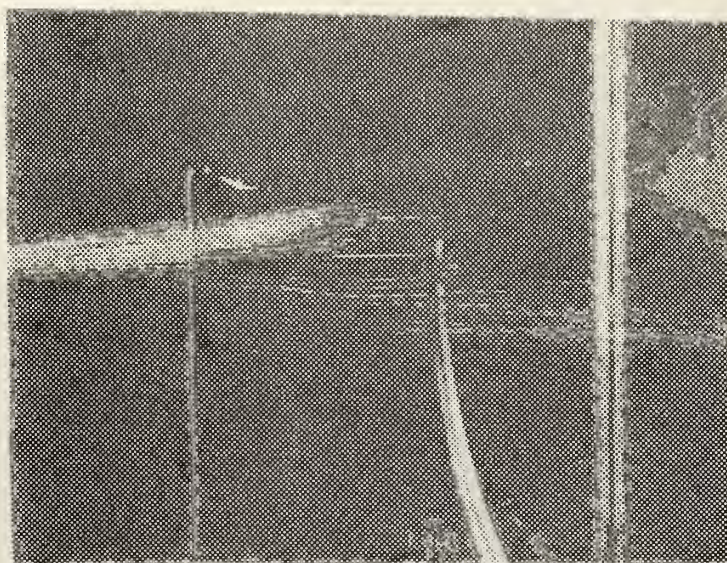


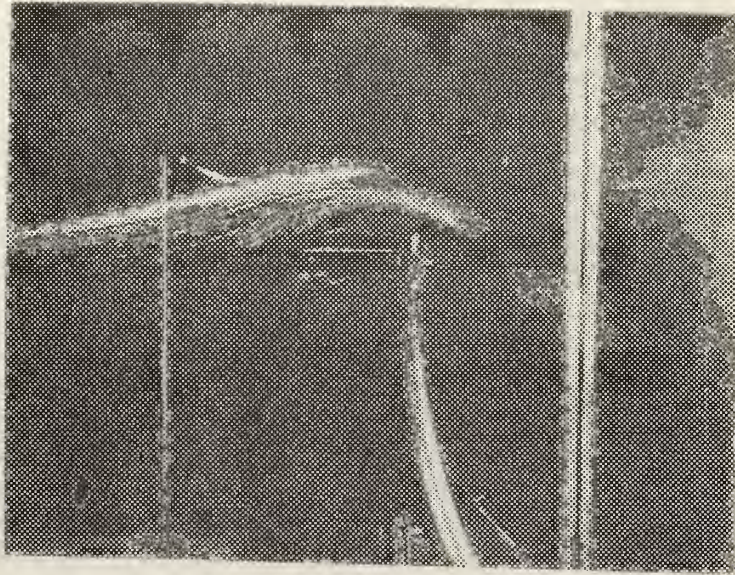
Figure 19. Smoke Flow. $V=13$ ft/sec. ; $C_j=0.0$

the lighting, part of the flow over the top downstream section of the wing cannot be seen. It was found that due to the narrow beams and low power of the three arc lamps used, the beams all had to be directed at one area of interest. Therefore, the whole flow field could not always be illuminated.

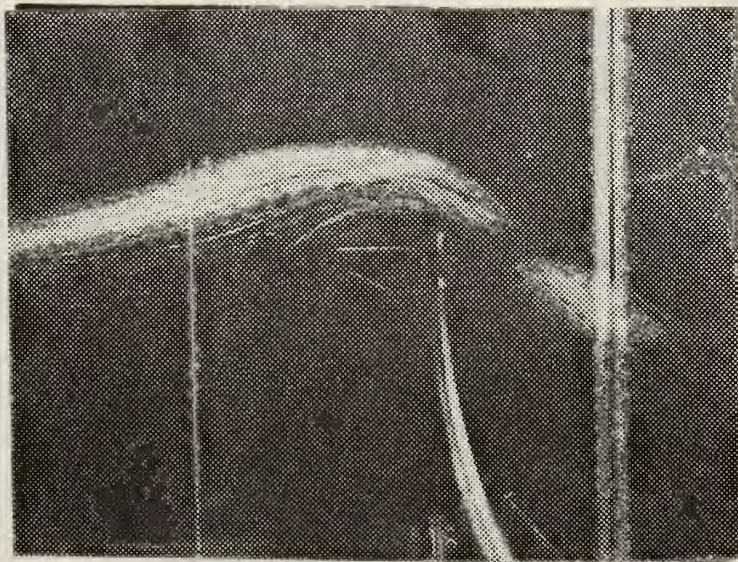
As mentioned previously, the position of the light beams was very important as can be seen in Figures 20-a,b where the two beams were directed over the top of the wing and one along the bottom in order to concentrate light in the region of possible separated flow on top. As a result of this new lighting arrangement an un-illuminated region appears just downstream of the trailing edge. In addition, Figures 20-a,b show the effects of the BFS and air settings. Both figures were taken at a 15-second exposure but 20-b was at a 0.2 less BFS and air setting.

Just as the BFS and air settings have a definite effect on the flow over a wing, so also does the ejector head position. Figure 21-a was the position used in the low-speed studies and Figure 21-b, a two-inch higher position, was used at the higher speeds. Since only one bubble generator head was available, it had to be positioned at a different height depending on what area of the wing was being studied. With more bubble generator heads this would be alleviated.

As mentioned previously, in order to get a picture of the flow over a wing with the helium bubble technique, the lens has to be held open for at least 15 seconds to get a fairly good picture with the present arc lamps used. Now in Figure 22 all three arc lamps were focused at the mid-chord point on the top of the wing and the shutter was held open for six

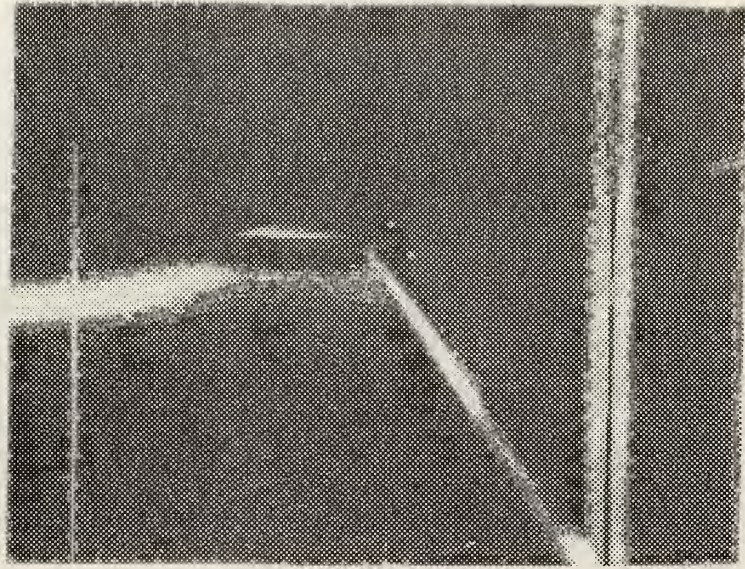


a. Helium Bubble Flow.



b. Helium Bubble Flow.

Figure 20. $V=13$ ft/sec. ; $C_j=7.4$



a. Helium Bubble Flow.



b. Helium Bubble Flow.

Figure 21. $V=32$ ft/sec. ; $C_j=1.2$

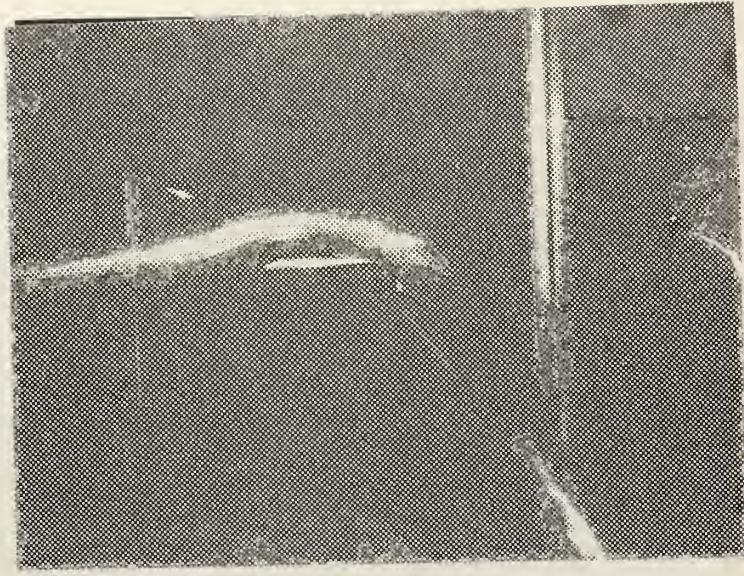
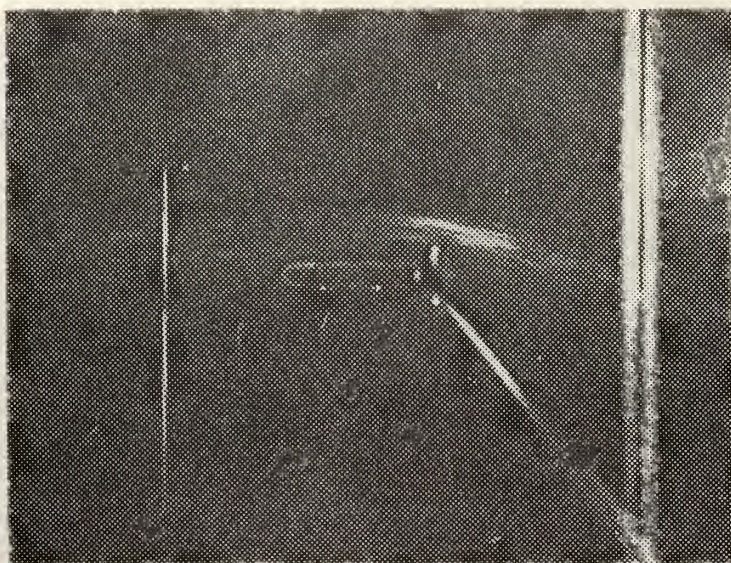


Figure 22. Helium Bubble Flow. $V=32\text{ft/sec.}$; $C_j=1.2$

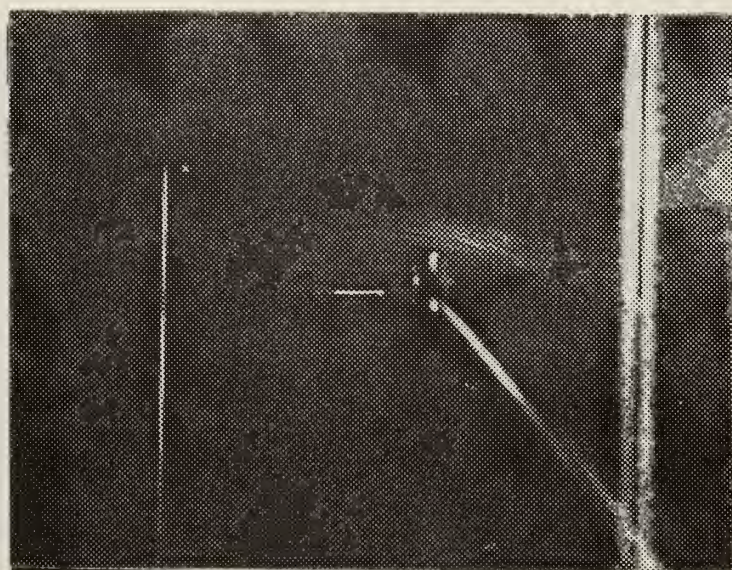
seconds. As can be seen, fairly good streamlines are evident as compared with Figures 16-b, 17-b, 18-b and 21-b, which were all taken at the high tunnel speed of 32 feet per second. This problem could be alleviated by a more powerful light source since then the shutter does not have to be left open as long.

Another problem encountered while photographing at the higher tunnel speed was that the wing over which the bubbles were flowing could not be seen. Therefore, exactly what was happening at the leading edge could not be seen, as is evident from Figures 16-b, 17-b, 18-b, 21 and 22. This problem was even more evident at the lower shutter speed values. To solve this problem reflective tape was put on the near edge of the wing as is seen in Figures 23, 24 and 25-a.

One of the best photographs taken in this study is shown in Figure 25-b. Here very well-defined streamlines can be seen over the entire model. Over the top rear section of the flap higher velocity lines can be seen. It should be noted that to produce this flow a slightly lower BFS setting was used than that used in the other photographs.

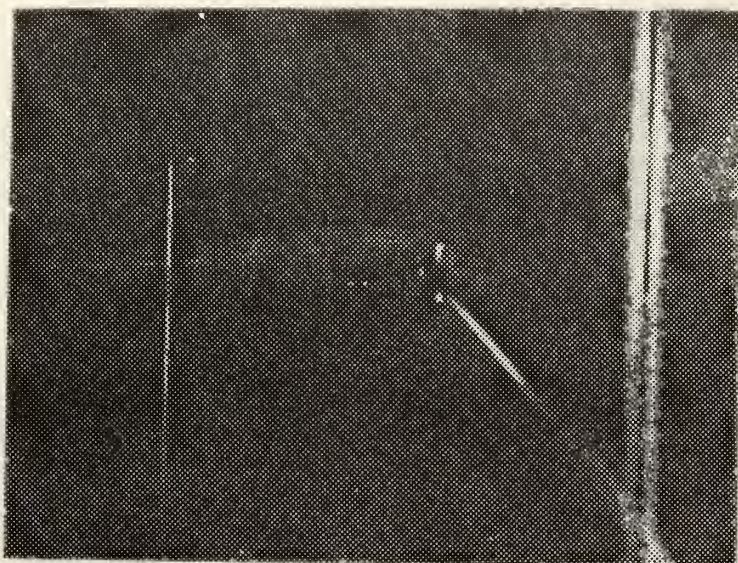


a. Helium Bubble Flow.Exposure=10 sec.

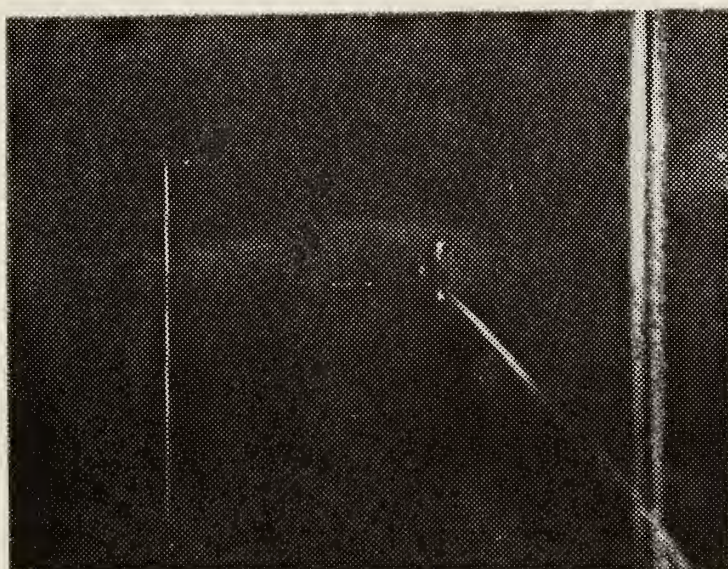


b. Helium Bubble Flow.Exposure=15 sec.

Figure 23. $V=32$ ft/sec. ; $C_j=1.2$

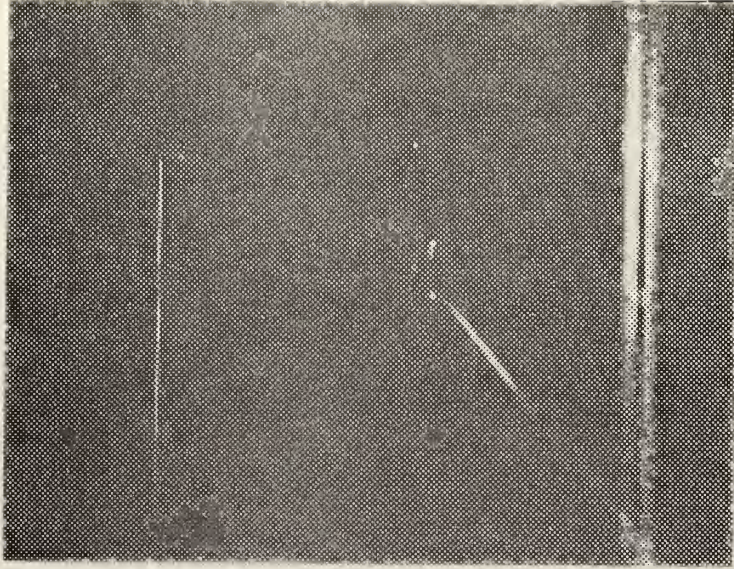


a. Helium Bubble Flow.Exposure=12 sec.

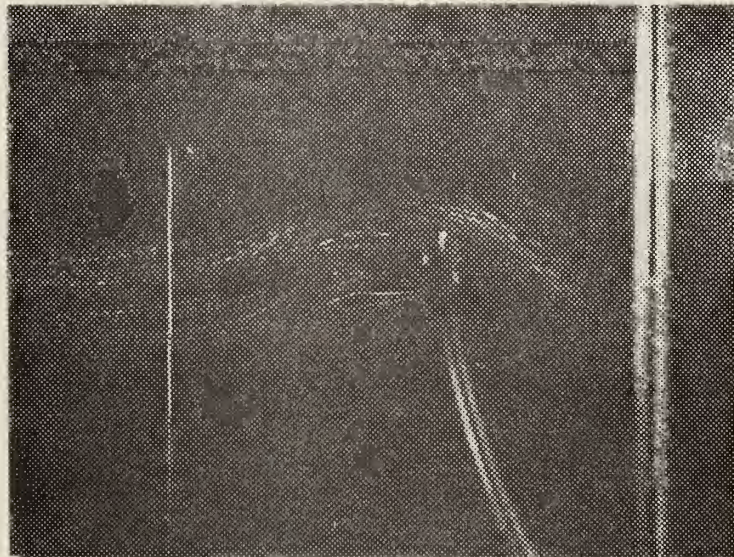


b. Helium Bubble Flow.Exposure=10 sec.

Figure 24. $V=32$ ft/sec. ; $C_j=0.7$



a. $V=32$ ft/sec. ; $C_j=1.2$; Exp.=8 sec.



b. $V=13$ ft/sec.; $C_j=7.4$; Exp.=15 sec.

Figure 25. Helium Bubble Flow.

VIII. CONCLUSIONS AND RECOMMENDATIONS

In this paper an exploratory investigation of the incompressible flow past a jet-flapped airfoil was described using two known flow visualization techniques. As a result of this study some basic conclusions can be drawn.

- 1) Even with the present turbulence and lighting in this tunnel it is still possible to get good smoke and helium bubble flow pictures.
- 2) The helium bubble technique was found to be much more convenient to work with in that one person could operate the generator and also take pictures, whereas two were required for the smoke flow technique.
- 3) With the present lighting systems it was found impossible to take movies of the helium bubble flow whereas it was possible to take 16-mm color movies of the smoke flow.
- 4) In this tunnel due to its size and high turbulence level, neither technique was good below a tunnel speed of six feet per second although Ringleb (Reference 3) worked with speeds between three and ten feet per second in a tunnel similar to this facility except there were six screens upstream of the test section.

- 5) From the photographs, it is felt that much more definition and contrast can be found overall in the helium bubble pictures.

In order to expand the usefulness of this facility for future investigation, the following recommendations are presented.

- 1) In order to reduce the turbulence of the facility, three more screens should be installed downstream of the honeycomb as recommended in Reference 7.
- 2) To reduce the glare from the present and future lights, the plexiglass observation window should be replaced with shatterproof non-reflective glass.
- 3) The full capability of the helium bubble technique has not really been explored because the present arc lamps are inadequate. The arc lamp recommended by Sage Action, Inc., (Ref. 11), or one similar to it, should be used.
- 4) A better overall lighting system should be considered for the facility, one that would allow the lights to be moved around outside the tunnel behind plexiglass or glass and thus not disturb the test section flow.

BIBLIOGRAPHY

1. Wick, B.H. and Kuhn, R.E., "Turbofan STOL Research at NASA," Astronautics and Aeronautics, p. 32-50, May 1971.
2. Simmons, J.M., and Platzler, M.F., "Experimental Investigation of Incompressible Flow Past Airfoils with Oscillatory Jet Flaps," Journal of Aircraft, Vol. 8, p. 587-592, August 1971.
3. Naval Air Engineering Laboratory Report NAEL-ENG-6818, The Three Dimensional Smoke Tunnel of the Naval Air Engineering Laboratory in Philadelphia, Pennsylvania, by Friedrich O. Ringleb, 10 July 1961.
4. North Atlantic Treaty Organization Advisory Group for Aeronautical Research and Development, AGARDOGRAPH ;70, Flow Visualization in Wind Tunnels using Indicators, by R.L. Maltby, April 1962.
5. Lippisch, A.M., "Flow Visualization," Aeronautical Engineering Review, p. 24-36, February 1958.
6. Princeton University Department of Aeronautical Engineering Report No. 290, Smoke Flow Studies Conducted at Princeton University, by D. C. Hazen and R. F. Lehnert.
7. Dryden, H.L. and Schubaur, G.B., "The Use of Damping Screens for the Reduction of Wind-Tunnel Turbulence," Journal of the Aeronautical Sciences, p. 221-228, April 1947.
8. Gorlin, S.M. and Slezinger, I.I., Wind Tunnels and their Instrumentation, p. 46-48, Israel Program for Scientific Translations, Ltd, 1966.
9. National Advisory Committee for Aeronautics, Technical Note No. 1283, The Langley Two-Dimensional Low Turbulence Pressure Tunnel, by A.E. VonDoenhoff and F.T. Abbot, 1947.
10. Rochester Applied Science Associates, Inc., RASA REPORT 71-01, An Experimental Study of Tip Vortex Modification by Mass Flow Injection, by S.A. Rinehart, J.C. Balcerak and R.P. White, p. 5-18, 46-50, 31 January 1971.
11. Sage Action, Incorporated, SAI Bubble Generator Model 3, by R. W. Hale, P. Tan and D.E. Ordway, March 1971.

12. University of Toronto Institute of Aerospace Studies Review No. 14, A Review of the Jet Flap, by G.K. Korbacher and K. Sridhar, p. 2-60, May 1960.
13. Spence, D.A., "The Lift Coefficient of a Thin, Jet-Flapped Wing," Proceedings of Royal Society A, Vol. 238, p. 46-63, 1956.
14. Dimmock, N.A., "Some Early Jet Flap Experiments," Aeronautical Quarterly, Vol. 8, Part 4, p. 331-345, November 1957.
15. Newman, B.G., "The Deflection of Plane Jets by Adjacent Boundaries - Coanda Effect," Boundary Layer and Flow Control, G.V. Lachmann, Pergamon Press, Vol. 1, p. 232-264, 1961.
16. Kind, R.J., "A Calculation Method for Circulation Control by Tangential Blowing a Bluff Trailing Edge," Aeronautical Quarterly, Vol. XIX, p. 205-223, August 1968.
17. Kind, R.J. and Maull, D.J., "An Experimental Investigation of a Low-Speed Circulation-Controlled Aerofoil," Aeronautical Quarterly, Vol. XIX, p. 170-182, May 1968.
18. West Virginia University Department of Aerospace Engineering, Analysis of a Circulation Controlled Elliptical Airfoil, by J. P. Ambrosiani and N. Ness, p. 1-8, 89-93, April 1971.
19. Pope, A., Wind-Tunnel Testing, p. 80-117, Wiley, 1954.
20. Williams, J. and Alexander, A.J., "Some Exploratory Three-Dimensional Jet-Flap Experiments," Aeronautical Quarterly, Vol. 8, Part 1, p. 21-30, February 1957.

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13. ABSTRACT An exploratory visualization study was performed on a jet-flapped airfoil in the Low Speed Flow Visualization Facility at the Naval Postgraduate School, Monterey, California. The purpose of this study was to evaluate the test facility for future work and to compare an old and a relatively new flow visualization technique. These techniques are smoke flow and helium bubble flow. The study was conducted using various tunnel speeds and blowing rates for the jet flap. The varying of these parameters and the complexity of the jet flap flow allowed for an excellent evaluation of the test facility and the two flow techniques. As a result of the many photographs taken, a comparison was made between predicted jet stream deflection, using Spence's Theory, and those deflections measured on photographs.			

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